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Assessing the costs of fossil dependency: an integrated model for carbon costs across economic sectors in China and Germany

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ABSTRACT

Fossil dependency has a significant cost impact on the economy, making sectors vulnerable to rising carbon costs. Economic sectors are impacted by carbon costs from two sides: fossil inputs and carbon emissions. The success of climate policy initiatives can depend upon carbon costs. The input side has not received sufficient attention. The article presents a model that integrates the fossil input and carbon emission sides to assess the total cost of carbon using input-output modelling. The model provides a comprehensive analysis of the total costs associated with fossil dependency. The integrated approach reveals the embodied carbon costs that accumulate in various economic sectors. The examples of China and Germany serve as illustrative cases due to their strong dependence on fossil inputs but different levels of climate policy enforcement. The research findings revealed that certain downstream industries, characterized by substantial embodied fossil inputs, may be more vulnerable to increased carbon pricing than upstream industries. Falling prices of fossil inputs may counterbalance the impact of rising carbon emission costs. The integrated model for assessing the total carbon cost enables policymakers to develop more efficient policies tackling climate change.

Key policy insights

- Policies related to fossil inputs are often developed independently of carbon emission policies. The two types of policy can be counterproductive if they are not integrated.
- Tightening emissions regulations could prove ineffective if fossil input prices fall.
- Due to spill-over effects, fossil input costs have a greater impact on certain downstream sectors, even if they are not directly targeted by carbon regulation.
- The cost of carbon emissions in the German economic sectors is much higher than in China. They are still negligible compared to fossil input costs in both countries. At current cost levels, emission allowances contribute little to the total costs of the economic sectors.

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Fossil inputs; embodied energy; carbon accounting; climate policy; embodied carbon emissions; input-output model

1. Introduction

The importance of fossil constraints in the economy is growing. Economic sectors are impacted both on the input side and on the output side (Busch & Hoffmann, 2007; Qin et al., 2023). On the input side, most sectors are heavily dependent on fossil resources. On the output side, carbon constraints manifest as costs

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incurred through carbon emission trading systems or carbon taxes (Markard & Rosenbloom, 2020; Rudnik et al., 2023). However, conflicts may arise between input-side and output-side policies. Falling fossil fuel prices can offset the impact of rising carbon costs, which can make fossil fuel use more economical. At the same time, rising fuel prices can provide incentives for sectors to become more energy efficient, even without taxing carbon emissions. The effect of energy policy on input prices and fossil resource use can impact the emission side (Choi et al., 2010). When policy initiatives are not well integrated, it can result in a behavior-impact gap problem, compromising the effectiveness of the latter, and creating a fragmented perspective on climate and energy policy (Blanchard et al., 2023; Csutora, 2012; Johnsson et al., 2019; Markard & Rosenbloom, 2020). As a result, progress towards decarbonization is hindered (Anke et al., 2020; Baranzini et al., 2017; Dominioni, 2022).

Several research studies analyzed the potential economic impact of fossil inputs and carbon emissions with various economic models. However, previous research, as presented in Section 2, did not assess the total monetary costs associated with both the input and output side of fossil dependency. The present research aims to address this research gap. It integrates both the input and output side costs of fossil dependence by input-output analysis. The cases of China and Germany serve as illustrations: both are influential players in climate policy, although the rigour of implementation is different. However, both are heavily dependent on fossil fuels. The model is based on environmentally extended input-output tables. Databases of OECD, CEAD and Eurostat are used for calculations.

The remainder of the article is organized as follows: a literature review on the accounting for embodied fossil inputs and carbon emissions is presented in Section 2. The third section outlines the proposed model and data utilized to account for total carbon costs. The fourth section applies the model to calculate total carbon costs using the case studies of the Chinese and German economies. The article concludes by discussing potential policy implications.

2. Literature review – accounting for carbon costs at the sectoral level

Dependency on fossils renders economic sectors vulnerable. Accounting for the related costs has emerged as a critical concern (Busch & Hoffmann, 2007; Schaltegger, 2018; Zhu et al., 2022). Internal carbon pricing is growing in popularity. By assigning hypothetical costs to their carbon emissions, companies can proactively prepare for potential regulatory tightening and prioritize investments in low-carbon projects (Bento & Gianfrate, 2020; Krueger et al., 2020). This practice is primarily motivated by external carbon constraints (Ben-Amar et al., 2022; Zhu et al., 2022).

While industries such as energy, paper, and air transportation often receive considerable attention in climate policy discussions (Brazzola et al., 2022; Wu, 2023; Yalew et al., 2020), the spillover effects on other sectors are less frequently addressed. However, an increasing number of sectors are now exposed to risks associated with carbon emissions (Capasso et al., 2020; Daumas, 2024). Several studies exist that quantify the spillover effects either on the fossil input side or on the carbon emission side by using input-output modelling. Environmentally extended input-output analysis related to the input side,quantifies the embodied energy use of economic sectors (Costanza, 1980; Odum, 2019). Accounting for embodied energy use can be applied at regional, national levels (Dobos & Tóth-Bozó, 2024), as well as on a global scale (Meng et al., 2023; Wu et al., 2020; Zhang & Li, 2024). Choi et al. (2010) used the example of carbon tax, and incorporated short-term, policy-driven changes into the input-output modelling to assess the policy's effects on the environment and economy.

The accumulation of fossil input costs can be observed on the input side, especially in downstream sectors that rely on carbon-intensive intermediate products and services. These costs may influence the market prices of products originating from carbon-dependent economic sectors (Andersson, 2020; Ivanova & Wieland, 2023). Downstream sectors are defined as manufacturing and service (or tertiary) sectors that utilize resources produced in the extractive industry, while upstream sectors are defined as extractive sectors (Eurostat, 2025). Accounting for embodied energy is particularly relevant in certain industrial sectors, as highlighted by Hong et al. (2019) and Zheng et al. (2023). Del Rio et al. (2022) emphasized energy dependence and associated costs of the pulp and paper sector and the steel industry. They highlighted that cost increases in fossil inputs can disproportionately impact these sectors. Downstream sectors may be more vulnerable to cost changes related to fossil resources than the energy sector itself, as the former often lack the ability to pass on these costs to consumers.

Based on the literature, the following research gaps were identified. Research studies using computable general equilibrium (CGE) models have examined the economic impacts of energy use and carbon emissions.

CGE models are excellent tools to represent interactions and feedback between economic sectors, and to calculate the macro-economic costs and impacts of energy policies through simulations (Fujimori et al., 2015). Dai et al. (2016) integrated global top-down and bottom-up models to compute scenarios for energy and carbon emission models in China, providing the first global model comparison with harmonized socio-economic assumptions for China. Dong et al. (2017) projected the potential impacts of carbon tax on carbon reduction and economic losses across 30 Chinese provinces, while Li et al. (2018b) created a CGE model to assess the effects of a regionally imbalanced carbon tax, estimating the influence of price effect and scale effect dominated by three markets. Some CGE models use input-output tables as inputs for calculations. Environmentally extended input-output analysis has a different purpose. It can be used to assess the embodied environmental impact by capturing the indirect emissions of economic sectors or the consumption of households across economic sectors. Several studies emphasized the importance of evaluating embodied emissions and spillover effects (Csutora & Vetőné Mózner, 2014; Dobos & Floriska, 2009; Pan et al., 2022b), however, they solely focused on the emission side, the fossil input side was not integrated into the analysis. These studies did not consider the cost impact of these embodied emissions either. In addition, several studies quantified the costs of carbon leakage and the abatement costs of embodied emissions, but they still overlooked the full costs of embodied carbon emissions (Chen et al., 2015; Fournier Gabela & Freund, 2023; Xia & Tang, 2017). None of the papers considered fossil inputs for non-energy use. Some sectors heavily rely on fossil inputs as feedstock. The agricultural and chemical industries stand out for their significant non-energy use of fossil inputs (Pimentel, 2019; Variani et al., 2023). The International Energy Agency's statistical system (IEA, 2019) provides a comprehensive classification of the energy and non-energy uses of fossil inputs.

An overview of previous research studies is presented in Appendix Table A.1.

It can be concluded that none of the studies using input-output analysis examined the carbon cost of both embodied fossil inputs (including non-energy use of fossil inputs) and the embodied carbon emission in one model. The model presented in this research attempts to fill the existing gap by integrating both the input and output sides of fossil resources within an economic model using environmentally extended input-output analysis. Overall, this integration allows for more informed decision-making regarding the management of fossil input dependency.

3. Model and methodology

3.1. Scope of the model, overview of carbon costs

The proposed model aggregates private carbon costs linked to fossil inputs and carbon emissions. On the input side, the model includes energy use from fossil inputs like coal, oil, and natural gas. The model also includes the non-energy use of fossil inputs, which refers to the use of fossil resources as raw materials to make various products, such as plastics, synthetic fibres, construction bitumen, and other chemical and petroleum-based goods in the petrochemical sector (IEA, 2019). The proposed model is built upon an environmentally extended input-output analysis (Leontief, 1970). This model utilizes input-output tables to capture the interdependencies between economic sectors and final use. These tables denote the sales and purchases of both final and intermediate goods and services and can be organized either based on industry outputs (industry by industry tables) or product outputs (product x product tables) (OECD, 2023). Leontief's model was later further developed into environmentally extended input-output tables (Bicknell et al., 1998; Ferng, 2001; Lenzen et al., 2007; Wiedmann et al., 2011). Leontief's model serves as a 'top-down' technique applicable to macro-level analyses at the international, national, and sectoral levels (Dobos & Tallos, 2013; Munksgaard et al., 2009; Tukker et al., 2020). Various input-output models exist, such as the single-region input-output model (Bai et al., 2024; Mózner, 2013; Södersten & Lenzen, 2020), the bilateral trade input-output model (Pan et al., 2022a; Wang & Yang, 2020), and the multi-region input-output model (e.g. Fry et al., 2022; Li et al., 2023; Yang et al., 2023).

Figure 1 illustrates our proposed model for the calculation of the carbon costs of embodied fossil inputs and carbon emissions linked to the final use of the sectors. It captures six types of costs associated with fossil use:

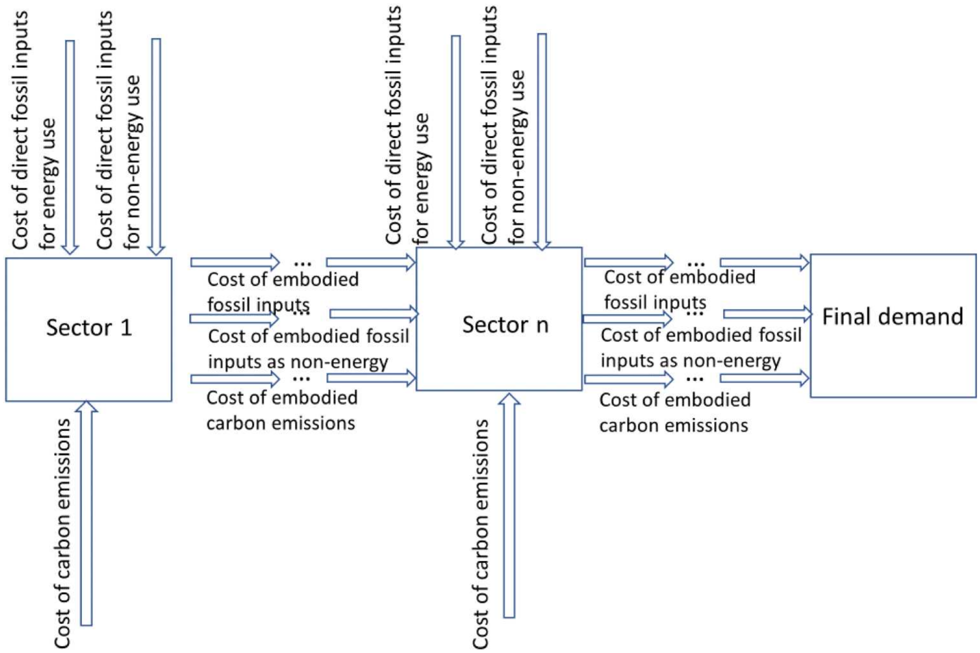

Figure 1. Overview of input and output-related carbon costs across economic sectors. Source: Authors' compilation based on OECD (2023).

- cost of direct fossil inputs for energy use
- cost of direct fossil inputs for non-energy use
- cost of carbon emission
- cost of embodied fossil input for non-energy use
- cost of embodied fossil inputs for energy use
- cost of embodied carbon emissions

None of the studies presented in the literature review examined all six cost elements simultaneously.

The analysis excludes biomass combustion, which is considered renewable and relatively carbon neutral (IEA, 2019). Furthermore, it excludes external costs that have not yet been internalized by economic sectors. Thus, the analysis does not cover the costs of mitigating damages caused by climate change events such as floods, as their likelihood is uncertain (IPCC, 2022). Additionally, the analysis does not include adaptation costs or the social cost of carbon emissions, which pertain to the impacts of increasing greenhouse gas emissions.

Previous analyses have focused primarily on the carbon emission side, which may lead to the development of policies that only address emission-related issues, and studies that have examined the impact of energy taxes have generally not taken into account the cost of pollution rights and the cost of non-energy fossil input use. The present model integrates the costs of fossil reliance on both input and output sides.

3.2. Proposed model for the integrated calculation of embodied carbon inputs and outputs

The proposed model rests upon monetary input-output tables, which illustrate the monetary flows that occur between different economic sectors.

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \tag{1}$$

where

- $\boldsymbol{x}$ is the vector of total economic output in each sector,
- $\boldsymbol{y}$ is the vector of final demand in each economic sector,

- $\boldsymbol{A}$ is the direct requirements matrix. It shows the quantity of inputs needed to produce one unit of output.

Rearranging equation (1) leads to

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{2}$$

where

- $\boldsymbol{I}$ is the identity matrix,
- $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix derived from (industry by industry) input-output tables. This portrays the input requirements of each industry required to produce an additional unit of output.

The Leontief inverse matrix provides information on both the direct and indirect input requirements, so it is a valuable tool for analyzing the interdependencies within an economy.

We extend the monetary input-output tables to incorporate fossil inputs and carbon emissions using physical units.

3.2.1. Calculating direct fossil inputs

When calculating embodied fossil inputs, the energy and non-energy use of fossil inputs are taken into account, as shown in equation (3). The amount of fossil inputs is measured in physical units (e.g. tons of oil equivalent) for each fossil input (coal, oil, and gas).

The vector $\boldsymbol{b_k}$ of fossil inputs is defined as

$$\boldsymbol{b_k} = \boldsymbol{b_{k,\,energy}} + \boldsymbol{b_{k,\,non-energy}} \tag{3}$$

where

- $\boldsymbol{b_k}$ is the vector of fossil inputs,
- k is the type of fossil inputs. The index $k = 1, \ldots, l$ corresponds to the type of fossil input,
- $\boldsymbol{b_{k,\,energy}}$ for each k, is the vector of direct fossil input used as energy for each economic sector,
- $\boldsymbol{b_{k,\,non-energy}}$ for each k, is the vector of direct fossil inputs used as non-energy.

In our case, three fossil inputs will be considered: coal, oil and natural gas, so $l = 3$.

3.2.2. Calculating fossil input coefficients

For each type of fossil input $k = 1, \ldots, l$, the direct carbon intensity of economic sectors ($\boldsymbol{f_k}$) can be determined by

$$\boldsymbol{f_k} = \boldsymbol{b_k} \langle \boldsymbol{x} \rangle^{-1} \tag{4}$$

where

- $\boldsymbol{f_k}$ is the vector of direct carbon intensity, where each component corresponds to an economic sector and provides the direct fossil input coefficients,
- $\boldsymbol{b_k}$ is the vector of fossil inputs,
- $\boldsymbol{x}$ is the vector of total output in each sector,
- $\boldsymbol{x}$ is the diagonalized matrix of vector $\boldsymbol{x}$.

In other words, each component of $\boldsymbol{f_k}$ for each k is the ratio of the corresponding component of $\boldsymbol{b_k}$ divided by the corresponding component of $\boldsymbol{x}$. Direct carbon intensity expresses the ratio of the direct fossil input and economic output for each economic sector.

The rows of the $l \times n$ matrix $\boldsymbol{F}$ are the row vectors $\boldsymbol{f_k}$. Matrix $\boldsymbol{B}$ consists of the row vectors $\boldsymbol{b_k}$ and

$$\boldsymbol{F} = \boldsymbol{B}\ \langle \boldsymbol{x} \rangle^{-1} \tag{5}$$

where

- $\boldsymbol{F}$ is the $l \times n$ matrix of direct fossil intensity,
- $\boldsymbol{B}$ is the $l \times n$ matrix of fossil input use,
- $\boldsymbol{x}$ is the vector of total output in each sector.

Table 1 shows economic-ecological commodity flows and matrix definitions where $\boldsymbol{h}$ is the vector of value-added in each sector, $\boldsymbol{B}$ is the $l \times n$ matrix of fossil input use.

3.2.3. Calculating embodied fossil inputs

The proposed model accounts for embodied fossil inputs across various economic sectors, considering all fossil input types. The embodied fossil input of an economic sector embraces both energy and non-energy use that is required to produce one unit of output.

The total embodied fossil input of economic sectors given in tons of oil equivalent can thus be quantified as

$$\boldsymbol{C_{inp}} = \mathbf{1}\ \boldsymbol{F}(\boldsymbol{I} - \boldsymbol{A})^{-1}\langle \boldsymbol{y} \rangle \tag{6}$$

where

- $\boldsymbol{C_{inp}}$ is the vector of embodied fossil input,
- $\mathbf{1}$ is the column vector of all 1s,
- $\boldsymbol{F}$ is the $l \times n$ matrix of direct fossil input intensities,
- $\boldsymbol{A}$ is the $n \times n$ matrix of technical coefficients (in other words, direct requirements),
- $\boldsymbol{y}$ is the vector of final demand, and
- $\boldsymbol{y}$ is the diagonalized matrix of vector $\boldsymbol{y}$**.**

3.2.4. Calculating direct emission coefficients

The next phase involves computing the embodied greenhouse gas (GHG) emissions of economic sectors employing the environmentally extended input-output model. Initially, the direct emission intensities are established for each type of GHG emissions $m = 1, \dots, q$.

$$\boldsymbol{e_m} = \boldsymbol{d_m}\langle \boldsymbol{x} \rangle^{-1} \tag{7}$$

where

- $\boldsymbol{e_m}$ is the vector of direct emission intensities,
- m is the index of GHG type,
- $\boldsymbol{d_m}$ is the vector of direct emissions,
- $\boldsymbol{x}$ is the vector of total output in each sector, and
- $\boldsymbol{x}$ is the diagonalized matrix of vector $\boldsymbol{x}$.

Table 1. Economic-ecological commodity flows – Matrix definitions.

Input-output	Intermediate use	Final demand	Total output
Intermediate input	**X**	**y**	**x**
Value added	**h**		
Total input	**x**		
Direct fossil input	**B**		
Direct carbon emissions	**D**		

Source: Authors' compilation based on Miller and Blair (2009).

The value of each component of $\boldsymbol{e_m}$ can be obtained by dividing the corresponding element in $\boldsymbol{d_m}$ by the corresponding element in $\boldsymbol{x}$. This direct emission intensity shows the amount of direct emission produced by each economic sector per unit of output.

For this analysis, m is set to 1 since reliable data were only available for CO_2 emissions. Other greenhouse gas emissions are not considered in the current assessment.

The rows of the $q \times n$ matrix $\boldsymbol{E}$ are the row vectors $\boldsymbol{e_m}$. Matrix $\boldsymbol{D}$ consists of the row vectors $\boldsymbol{d_m}$ and

$$\boldsymbol{E} = \boldsymbol{D}\langle \boldsymbol{x} \rangle^{-1} \quad (8)$$

where

- $\boldsymbol{E}$ is the $q \times n$ matrix of direct carbon intensity,
- $\boldsymbol{D}$ is the $q \times n$ matrix of carbon emissions, and
- $\boldsymbol{x}$ is the vector of total output in each sector.

Table 2 depicts the direct impact coefficients in the environmental input-output analysis.

3.2.5. Calculating embodied carbon emissions

The embodied carbon emissions are calculated as follows:

$$\boldsymbol{C_{em}} = \boldsymbol{1E}(\boldsymbol{I} - \boldsymbol{A})^{-1}\langle \boldsymbol{y} \rangle \quad (9)$$

where

- $\boldsymbol{C_{em}}$ is the vector of embodied carbon emissions,
- $\boldsymbol{1}$ is the vector of all 1s,
- $\boldsymbol{A}$ is the $n \times n$ input-output matrix of technological coefficients,
- $\boldsymbol{y}$ is the vector of final demand, and
- $\boldsymbol{y}$ is the diagonalized matrix of the vector $\boldsymbol{y}$.

3.2.6. Calculating total carbon costs

To calculate the economic sectors' total carbon cost, we multiply the embodied fossil inputs and embodied carbon emissions by their respective prices. Thus, the total carbon costs encompass the aggregate cost of both fossil inputs and GHG emission outputs.

Correspondingly:

$$\boldsymbol{C_{cost}} = \boldsymbol{pF}(\boldsymbol{I} - \boldsymbol{A})^{-1}\langle \boldsymbol{y} \rangle + \boldsymbol{rE}(\boldsymbol{I} - \boldsymbol{A})^{-1}\langle \boldsymbol{y} \rangle \quad (10)$$

where

- $\boldsymbol{C_{cost}}$ is the vector of the total carbon cost for each economic sector,
- $\boldsymbol{p}$ is the vector of input prices for each fossil input type, and
- $\boldsymbol{r}$ is the price vector of carbon emissions.

Fossil input prices ($\boldsymbol{p}$) reflect the actual market rates for each input. Carbon emission prices ($\boldsymbol{r}$), following Hoffman and Busch, are based on actual market prices, using the average emission allowance price as a

Table 2. Direct impact coefficients in the environmental input-output analysis.

Input-output	Intermediate use	Final demand	Total output
Intermediate input	**A**	**y**	**x**
Value added	**h**		
Total input	**x**		
Direct fossil input intensity matrix	**F**		
Direct carbon emission intensity matrix	**E**		

Source: Authors' compilation based on Miller and Blair (2009).

proxy. The emission allowance prices were €7.1 per ton in China and €24.5 in Germany in 2019. This article extends this proxy pricing to sectors outside current emission trading schemes. However, as more sectors join emission trading systems, these shadow prices could soon become real market prices.

3.3. Sources of data

We illustrate our model with a comparative analysis of China and Germany using the latest OECD Structural Analysis of National Accounts (STAN) input-output tables (OECD, 2023). Our analysis includes 45 economic sectors categorized using the OECD's ISIC Rev. 4 classification. For China, sector-specific fossil input data were sourced from the CEAD official website (Guan et al., 2021; Shan et al., 2018, 2020), which provides comprehensive data on the energy and non-energy use of sectors. The latest data available was for the year 2019. The relevance of non-energy use stems from the role of fossil inputs as raw materials in several industries, as noted by Li et al. (2018a). All fossil inputs were standardized to tons of oil equivalent (toe) using the UN Energy Balances Conversion factors (UN, 2021).

The national CO_2 emissions inventory for China, sourced from the CEADs database and categorized by IPCC sectoral emissions, served as the database for the emission analysis (Guan et al., 2021; Shan et al., 2018, 2020;). Due to the reported uncertainties in the availability of non-CO_2 GHG emission data in China (Wang et al., 2018) our current study was limited to CO_2 emissions.

For Germany, we extracted data on the fossil input use of economic sectors by fossil input type from the Eurostat database: Complete energy balances (Eurostat, 2023a). These fossil inputs were quantified in physical units – specifically, tons of oil equivalent (toe). The carbon emission statistics were sourced from the Air emissions accounts database in Eurostat (2023b).

We acquired fossil input prices for oil, natural gas, and coal from the International Energy Agency's dataset on Energy Prices and Taxes (2022), adopting a single average price for each type of fossil input for simplicity, although in practice, prices can differ by sector.

Emission costs were based on the average price taken from the China National Emissions Trading System (Icapcarbonaction, 2023) and, for Germany, the EU Emissions Trading System (EU ETS, 2023).

4. Results and discussion

This section outlines the findings from applying our model to China and Germany. Both countries are highly dependent on fossil inputs, and both are prominent players in environmental policy: China as the top GHG emitter in the world and Germany as declared leader in climate policy implementation. Germany is further ahead in the implementation of ETS, while China has started to implement its own version recently. It is interesting to look at how the cost of carbon emission rights and the cost of fossil inputs, as a whole, affects the costs of economic sectors in the two countries with different advancement levels of emission trading. This can serve as a good starting point for future studies, e.g. to compare the impact on competitiveness or the impact of input and output side environmental policies.

The case of China is particularly noteworthy due to its substantial reliance on fossil inputs: coal accounts for 61% of its energy supply. Net imports account for 20.7% of its total energy supply, China exhibits significant energy import dependency (IEA, 2025). It is a leading emitter of greenhouse gases in the world and exhibits the largest energy deficit globally (Wang et al., 2023). Germany positions itself as a forerunner in international climate policy. It participates in the EU Emissions Trading System and has even implemented a national carbon pricing mechanism for non-EU-ETS sectors such as transportation and heating. Germany is also known for its substantial energy transition efforts (Energiewende), however, it is still heavily dependent on fossil fuels. 77% of its energy consumption in 2019 came from fossil sources and it imports 71% of its energy (Bang et al., 2022).

4.1. Embodied fossil inputs in China and Germany

We quantified direct fossil inputs for both energy and non-energy purposes using equation (3). In the non-energy category, oil and its byproducts stand out, accounting for 52% of usage in China, and 90% in

Germany. (Results can be seen in Appendix Figure A.1. and A.2.) The main sectors with a high share of non-energy use are similar in China and in Germany: 'Rubber and plastic products sector' uses oil for non-energy use, while the sector 'Coke and refined petroleum products' sector uses both coal and oil as inputs. In China, 'Chemicals and chemical products', and 'Rubber and plastic products' are significant non-energy consumers of coal, accounting for 44% of non-energy use.

Based on Equation (6), the calculation proceeded by obtaining embodied fossil inputs for energy and non-energy purposes. The findings, illustrated in Figure 2, indicated that embodied fossil inputs in China's downstream sectors are two to three times higher than direct carbon inputs. This is particularly significant in sectors like 'Manufacturing'; 'Computer, electronic, and optical equipment manufacturing', and 'Electrical equipment production'. They are not typically perceived as major primary energy users, but rather large users of electricity, so their fossil input use is hidden in the direct fossil inputs of the 'Electricity, steam and gas sector'. 'Textiles, textile products, leather, footwear industry', 'Construction', and various service sectors (e.g. 'Art, and entertainment', 'Human health and social work activities' and 'Public administration and defence') are also associated with an unexpectedly high embodied fossil input compared to their direct fossil input requirements. In the 'Construction' sector, the demand for transport and material handling and the associated energy use is huge and is reflected in direct inputs from other sectors. The 'Textiles, textile products, leather, footwear industry is a significant consumer of plastics, which are non-energy fossil inputs. The significance of embodied non-energy fossil inputs in the sector is substantial.

Conversely, upstream sectors account for less embodied fossil inputs than direct ones. These industries pass on the fossil inputs embodied in their products to downstream sectors. Notable sectors include 'Coke and refined petroleum products', 'Chemicals and chemical Products'. The sum of direct carbon inputs across economic sectors equals the sum of embodied carbon inputs across the same sectors.

In the case of Germany (Appendix Figure A.3.) embodied carbon inputs exceeded far direct carbon input use in sectors like 'Motor vehicles, trailers and semi-trailers', 'Other transport equipment, and manufacturing'. Sectors like 'Rubber and plastics products', and 'Other non-metallic mineral products' pass on their input requirements to downstream sectors. A comparison of the results revealed that the 'Other transport equipment, and manufacturing sector' had high embodied carbon inputs in both Germany and China. There is a substantial difference in the level of embodied carbon inputs between the two countries, with China, being a larger

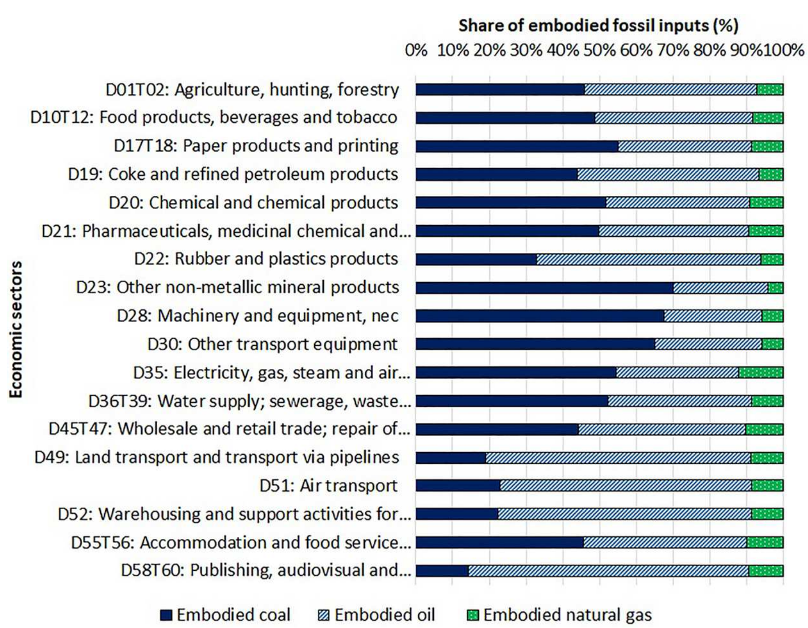

Figure 2. Embodied fossil inputs of selected economic sectors in China.

economy, exhibiting a greater overall use of fossil inputs. Fossil dependency impacts economic sectors from two sides: economic sectors pay for fossil inputs, and they are also impacted by carbon emission costs.

4.2. Embodied carbon emissions in China and Germany

The total embodied CO_2 emissions in China and Germany were determined using the formula outlined in equation (9), as shown in Appendix Table A.2. The sectors that stand out in China due to their substantial embodied emissions include 'Manufacturing'; 'Electrical equipment' and 'Other transportation equipment manufacturing', as well as the 'Computer and electronic equipment industry'. The sectors characterized by elevated embodied emissions closely resemble those with significant embodied fossil inputs; however, a distinction exists since the major plastic-utilizing sectors like 'Rubber and plastic products sector' are absent from this list. In 'Electricity, gas, steam, and air conditioning' sector direct CO_2 emissions exceed embodied emissions. It provides inputs for downstream sectors, thereby pass on embodied emissions to downstream industries. China is a major importer of raw materials, and it transfers embodied emissions to extractive industries in other countries.

In Germany, embodied carbon emissions are high for 'Manufacturing sector', 'Real estate activities', 'Electrical equipment' and 'Machinery and equipment' sectors. Lower embodied emission values were revealed for upstream sectors like 'Warehousing and support activities for transportation', 'Postal and courier activities' and 'IT and other information services'. Results for both countries show that certain sectors are more impacted on the input side and others on the output side when accounting for embodied fossils. The share of embodied emissions is relatively higher in the 'Manufacturing' sector in both countries.

4.3. Total carbon costs of economic sectors in China and Germany

Table 3 presents the total carbon costs of selected Chinese sectors, while Appendix Table A.3. shows the same for Germany, calculated as per equation (10).

The cost of embodied fossil inputs exceeded the costs of embodied carbon emissions across all sectors in both countries. In several sectors costs of embodied fossil inputs represented more than 90% of total carbon costs. The substantial presence of embodied non-energy oil in these sectors contributes significantly to their high level of embodied carbon inputs. 'Electricity' and other energy-related industries face a dual challenge in both countries, due to their unique position of having energy as the output of their production activities rather than an input. They may experience the impact of rising CO_2 costs but may also be adversely affected by any reduction in electricity prices. Unlike other sectors, these sectors are benefiting from the rise in energy prices.

The total carbon cost in China was higher than in Germany because China is a larger economy. With the exception of the 'Electricity, gas, steam, and air conditioning supply sector', fossil input costs constitute the largest portion of the total carbon cost for all sectors in both countries. These sectors account for large shares in both countries: 'Chemicals and chemical products', 'Rubber and plastic products' and 'Coke and refined petroleum products'. In China, 'Water transport' accounted for high fossil input costs compared to total carbon costs. In Germany, 'Land transport' and 'Warehousing and support activities for transportation' accounted for a high share. The 'Agriculture sector' had a significant share of total input costs in both countries due to its use of non-fossil inputs.

A key driver of the high share of fossil input costs is the low price of emission allowances. The average price between 2021 and 2023 was 7.6 USD/t in China, while 24.5 EUR/t in Germany, which is higher than in China, but still not high enough. Projections indicate that as carbon prices rise, the proportion of emission costs in total carbon costs is likely to surge. Should the emission price double, sectors such as 'Electricity, gas, steam, and air conditioning supply', the 'Water supply' industry would face increased CO_2 emission costs.

Research findings unveil that some downstream industries characterized by substantial embodied fossil inputs might be more susceptible to higher carbon costs than upstream industries. Some upstream industries can successfully pass on their costs to downstream industries, so an integrated approach is needed to analyze the interplay between economic sectors.

Table 3. Total Chinese carbon costs (million USD).

Economic sectors	Cost of fossil inputs	Cost of carbon emissions	Total carbon cost	Fossil input cost/total carbon cost
D01T02: Agriculture, hunting, forestry	6266	1401	7666	82%
D10T12: Food products, beverages and tobacco	10461	2470	12932	81%
D17T18: Paper products and printing	703	186	889	79%
D19: Coke and refined petroleum products	3571	358	3930	91%
D20: Chemical and chemical products	1279	196	1476	87%
D21: Pharmaceuticals, medicinal chemical and botanical products	1980	471	2450	81%
D22: Rubber and plastics products	2515	341	2856	88%
D23: Other non-metallic mineral products	2223	808	3031	73%
D28: Machinery and equipment, nec	15249	4603	19852	77%
D30: Other transport equipment	3234	936	4170	78%
D35: Electricity, gas, steam and air conditioning supply	3648	11478	15126	24%
D36T39: Water supply; sewerage, waste management and remediation activities	1071	440	1511	71%
D45T47: Wholesale and retail trade; repair of motor vehicles	4348	1054	5403	80%
D49: Land transport and transport via pipelines	5890	1345	7236	81%
D51: Air transport	236	39	275	86%
D52: Warehousing and support activities for transportation	1055	179	1234	86%
D55T56: Accommodation and food service activities	3243	876	4119	79%
D58T60: Publishing, audiovisual and broadcasting activities	1560	321	1881	83%

Table 4 illustrates the relative shares of carbon emission costs to total carbon costs and the relative share of carbon emission costs to total industry output across selected sectors in China and in Germany.

The total costs of carbon emissions may effect several downstream sectors that are not explicitly subjected to climate polices. Even in Germany, the share of emission costs to the sector's output cost is very low for most sectors. In China, the values are even lower for all sectors. This implies that climate policy, which focuses on emission costs, has a rather low impact on the total industry costs. Fossil input costs have a greater impact on the competitiveness of these sectors, although they might be overlooked in climate policy debates. Consequently, any impact of climate policy on the emissions side could be quickly offset by a reduction in input prices.

Table 4. Relative share of carbon emission costs to total carbon costs and relative share of carbon emission costs to total industry output, in China and Germany

	Carbon emission cost/ total carbon cost		Carbon emission cost/ output	
Economic sectors	China	Germany	China	Germany
D01T02: Agriculture, hunting, forestry	18%	19%	0.07%	0.3%
D10T12: Food products, beverages and tobacco	19%	41%	0.14%	1.9%
D17T18: Paper products and printing	21%	20%	0.04%	0.3%
D19: Coke and refined petroleum products	9%	15%	0.06%	0.5%
D20: Chemical and chemical products	13%	10%	0.01%	0.4%
D21: Pharmaceuticals, medicinal chemical and botanical products	19%	13%	0.12%	0.4%
D22: Rubber and plastics products	12%	6%	0.06%	0.2%
D23: Other non-metallic mineral products	27%	28%	0.08%	0.6%
D28: Machinery and equipment, nec	23%	17%	0.37%	0.3%
D30: Other transport equipment	22%	17%	0.42%	0.2%
D35: Electricity, gas, steam and air conditioning supply	76%	67%	1.14%	1.4%
D36T39: Water supply; sewerage, waste management and remediation activities	29%	28%	0.22%	0.1%
D45T47: Wholesale and retail trade; repair of motor vehicles	20%	27%	0.05%	0.4%
D49: Land transport and transport via pipelines	19%	2%	0.15%	0.2%
D51: Air transport	14%	32%	0.03%	2.0%
D52: Warehousing and support activities for transportation	14%	8%	0.10%	0.1%
D55T56: Accommodation and food service activities	21%	30%	0.14%	0.6%
D58T60: Publishing, audiovisual and broadcasting activities	17%	16%	0.38%	0.1%

5. Conclusions and policy implications

The cost of carbon inputs follows the price of fossil inputs, while the cost of carbon emissions is influenced by climate policy. The costs of fossil inputs and carbon emissions can move in different directions, so an integrated policy is needed to influence sectoral fossil dependence, addressing both the input and output sides. The carbon cost accounting models used so far do not sufficiently support the implementation of an integrated policy.

The article introduced a model that integrated the fossil input and carbon emission sides to assess the total cost of carbon across economic sectors. The model uses input-output modelling exemplified by China and Germany. It includes both the energy and non-energy use of fossil inputs and their associated costs, as well as emission costs. The integration of both fossil input- and emission side carbon accounting has significant benefits for policy. It provides a comprehensive understanding of the total costs associated with fossil dependency. By including the non-energy use of fossil inputs, the model improves the accuracy of carbon accounting.

Our research findings revealed that costs related to embodied fossil inputs outweigh the costs of embodied carbon emissions in the total costs of economic sectors at recent prices. Falling prices of fossil inputs can potentially undermine the effectiveness of carbon emission policies. Focusing on emissions regulations alone may prove ineffective if the trends in input prices counteract this. The success of the Paris Agreement and climate mitigation policies largely depends on the implementation of appropriate carbon pricing mechanisms. The integrated model may contribute to the effectiveness of carbon emission policies. The results of total embodied carbon cost accounting can help understand how different sectors are affected by uncoordinated changes in input and output carbon prices. The impact of these changes can vary significantly across sectors. While a comprehensive scenario analysis is beyond the scope of this article, we've shed light on potential policy conflicts between energy policy and climate policy. A successful transition to a low-carbon economy requires high total carbon costs, including both fossil input and emission costs. Sectors with high total carbon costs tend to respond better to policy interventions. Emission policies should use scenario analysis based on models integrating both the input and output sides of fossil dependency. Carbon policy practice should increasingly rely on carbon accounting studies to enhance its effectiveness.

In Germany, the share of carbon emission costs to total output is greater than in China, hence increasing sectoral costs. As China's carbon emission regulation is still relatively recent, carbon costs of embodied emissions represent a smaller share of the total output across economic sectors. At the same time, only a few sectors in Germany exhibit substantial carbon costs of embodied emission compared to total output. In both countries, it is the cost of embodied fossil inputs that account for the majority of total carbon costs. Therefore, the total costs of sectors are not much affected by climate policy, which aims to reduce emission costs.

The integrated approach accurately identified the embodied carbon costs that accumulate from extractive sectors to manufacturing and tertiary sectors. Therefore, more emphasis should be placed on estimating the costs of fossil inputs and carbon emissions in the tertiary and manufacturing sectors.

Several limitations of our research should be acknowledged. The analysis on the emission side could include non-CO_2 GHG emissions if reliable data were available. In estimating embodied emission costs, the methodology incorporates the cost of carbon emission allowances as the shadow price for those sectors not yet included in the emissions trading scheme. As data for fossil inputs, data for CO_2 emissions, and input-output tables are accessible to numerous countries, the analysis conducted in this study has the potential to be extended to other countries.

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Author contributions

CRediT: **Zsófia Vetőné Mózner:** Formal analysis, Writing, Visualization, Project administration; **Imre Dobos:** Validation, Writing; **Mária Csutora:** Conceptualization, Methodology, Visualization, Writing, Funding, Supervision.

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